

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Research Laboratory Washington, D.C. 20390		2a. REPORT SECURITY CLASSIFICATION Unclassified	
		2b. GROUP	
3. REPORT TITLE ELECTRON-PARAMAGNON INTERACTION EFFECTS IN NEARLY FERROMAGNETIC METALS			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final report on one phase of a continuing NRL Problem			
5. AUTHOR(S) (First name, middle initial, last name) A. I. Schindler			
6. REPORT DATE May 21, 1970		7a. TOTAL NO. OF PAGES 26	7b. NO. OF REFS 41
8a. CONTRACT OR GRANT NO. NRL Problem MO1-10		9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7057	
b. PROJECT NO. RR 007-01-46-5408		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
c.			
d.			
10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; its distribution is unlimited.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Department of the Navy, Office of Naval Research, Washington, D.C. 20360	
13. ABSTRACT The effects of itinerant spin-density fluctuations, or paramagnons, on various physical properties including the electronic specific heat coefficient γ , the low temperature electrical and thermal resistivities, and the ideal Lorenz number were reviewed. Paramagnon interaction effects, which are important in determining the low-temperature properties of strongly-exchange-enhanced paramagnetic metals like palladium, can be strongly modified by alloying additions, in particular nickel. The exchange enhancement increases with nickel content until, at some critical composition, the system goes ferromagnetic. Two models have been introduced to explain the properties of such alloys. In the one model, the uniform enhancement model, it is assumed that the effect of alloying with nickel may be represented by an increase in the exchange enhancement of the matrix. In the other model, the local enhancement model, the alloy is treated in a scheme valid in the dilute limit, where the spatial inhomogeneities of the spin density fluctuations in the vicinity of the nickel site are taken into account. Both of these models were examined and compared with experimental observations of Pd, Pt, and Rh with alloying additions of Ni. The theoretical calculations of various composition-dependent and temperature-dependent effects gave, in almost all cases, reasonable, but somewhat large, estimates for their magnitudes.			

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Metals Alloys Paramagnetic materials Low temperature research Platinum alloys Palladium alloys Rhodium alloys Nickel containing alloys Electrical resistivity Specific heat Ferromagnetism Exchange enhancement Many body effects						

CONTENTS

Abstract	ii
Problem Status	ii
Authorization	ii
INTRODUCTION	1
LOW-TEMPERATURE SPECIFIC HEAT	4
Theory	4
Experimental Results	6
ELECTRON TRANSPORT PROPERTIES	11
Theory	11
Experimental Results	14
SUMMARY	17
ACKNOWLEDGMENTS	20
REFERENCES	21

ABSTRACT

The effects of itinerant spin-density fluctuations, or paramagnons, on various physical properties including the electronic specific heat coefficient γ , the low temperature electrical and thermal resistivities, and the ideal Lorenz number were reviewed. Paramagnon interaction effects, which are important in determining the low-temperature properties of strongly-exchange-enhanced paramagnetic metals like palladium, can be strongly modified by alloying additions, in particular nickel. The exchange enhancement increases with nickel content until, at some critical composition, the system goes ferromagnetic. Two models have been introduced to explain the properties of such alloys. In the one model, the uniform enhancement model, it is assumed that the effect of alloying with nickel may be represented by an increase in the exchange enhancement of the matrix. In the other model, the local enhancement model, the alloy is treated in a scheme valid in the dilute limit, where the spatial inhomogeneities of the spin density fluctuations in the vicinity of the nickel site are taken into account. Both of these models were examined and compared with experimental observations of Pd, Pt, and Rh with alloying additions of Ni. The theoretical calculations of various composition-dependent and temperature-dependent effects gave, in almost all cases, reasonable, but somewhat large, estimates for their magnitudes.

PROBLEM STATUS

This report completes one phase of the problem; work on other aspects of the problem is continuing.

AUTHORIZATION

NRL Problem MO1-10
Project RR 007-01-46-5408

Manuscript submitted January 20, 1970.

ELECTRON-PARAMAGNON INTERACTION EFFECTS IN NEARLY FERROMAGNETIC METALS

INTRODUCTION

The concept of electron-electron interactions in strongly paramagnetic metals was first phenomenologically introduced by Stoner (1) to explain the large magnetic susceptibilities exhibited by certain transition metals and alloys. At that time the free electron theory of metals was being applied extensively, and it appeared that information concerning the density-of-states curves appropriate to pure metals and alloys could be obtained directly from experimentally determined values of the electronic specific heat and the magnetic susceptibility. According to the quantum mechanical, noninteracting electron theory of metals the coefficient γ of the linear term of the low-temperature specific heat is given by

$$\gamma = \frac{2\pi^2 k_B^2}{3} N_0(E_F) , \quad (1)$$

where $N_0(E_F)$ is the density of states per spin direction at the Fermi energy. Furthermore, according to the simple theory the "Pauli" paramagnetic susceptibility χ_0 is given by

$$\chi_0 = 2\mu_B^2 N_0(E_F) , \quad (2)$$

where μ_B is the Bohr magneton value.

Starting from these two equations, a self-consistent interpretation was given for the values of the density of states and for the manner in which the density of states values varied with alloying. For the alloys the rigid band model was tacitly assumed, and for the more strongly paramagnetic metals the Pauli susceptibility was generally assumed to be the dominant contribution.

For the simple, nontransition metals these notions fit the experimental facts tolerably well; for alloys these notions fit the data less well. However, the model breaks down rather badly when applied to the data of the strongly paramagnetic, transition metals Pd, Pt, and Rh. If one attempts to calculate the magnetic susceptibility of these transition metals by employing Eq. (2) along with an $N_0(E_F)$ obtained from Eq. (1) and experimental specific heat data, then one finds that the predicted magnetic susceptibility is too small by a factor as large as 10. A similar comparison with theory of the experimental values of the magnetic susceptibility and of the electronic specific heat coefficients for alloys of strongly paramagnetic transition metals also yields poor agreement.

This poor agreement was phenomenologically rectified by Stoner by postulating an internal molecular field λM proportional to the magnetization; the molecular field yielded an enhanced d-band polarization and, consequently, an enhanced magnetic susceptibility:

$$M = \chi_0(H + \lambda M) = \chi H , \quad (3)$$

from which

$$\chi = \chi_0 / (1 - \lambda \chi_0)$$

or

$$\chi = S \chi_0 ,$$

where χ is the "enhanced" susceptibility resulting from the additional polarization of the molecular field. S is the Stoner enhancement factor and is greater than 1 for strongly paramagnetic metals. The origin of the molecular field is not clear from this model, since it is essentially phenomenologically introduced, but it represents an interaction term favoring parallel electron spin alignment. The strength of this interaction can be deduced from the magnitude of $\lambda \chi_0$; when $\lambda \chi_0 = 1$, the susceptibility diverges and ferromagnetism occurs.

More recently (2) enhanced d-band polarization and magnetic susceptibility have been derived by introducing in the Hamiltonian a term representing a short-range intra-atomic repulsion between d-electrons of opposite spin states on the same Wannier orbital. In the equation

$$H_0 = T + I \sum_i n_{i\uparrow} n_{i\downarrow} , \quad (4)$$

where

$$n_{i\uparrow} = c_{i\uparrow}^\dagger c_{i\uparrow} ,$$

T is the kinetic energy term, $n_{i\uparrow}$ is the number operator for d-electrons with spin up associated with the i th unit cell, $c_{i\uparrow}^\dagger$ and $c_{i\uparrow}$ create or annihilate a spin-up electron in the Wannier orbital associated with the i th unit cell, and I is a measure of the phenomenological intra-atomic electron-electron repulsion between electrons of opposite spin. The s-electrons are presumed to provide sufficient shielding so that *inter*-atomic interactions are unimportant.

The consequences of the interactions between d-electrons have been determined in terms of a generalized susceptibility which is a function of the frequency ω and the momentum \mathbf{q} . Within the framework of the random phase approximation it can be shown that the generalized susceptibility $\chi(\mathbf{q}, \omega)$ for the exchange-enhanced metal can be obtained in terms of the generalized susceptibility for a noninteracting electron gas, $\chi_0(\mathbf{q}, \omega)$:

$$\chi(\mathbf{q}, \omega) = \frac{\chi_0(\mathbf{q}, \omega)}{1 - I \chi_0(\mathbf{q}, \omega)} . \quad (5)$$

The measured bulk susceptibility in this model is the value of χ at the static limit, $\mathbf{q} \rightarrow 0$ and $\omega \rightarrow 0$:

$$\chi(0, 0) = \frac{\chi_0}{1 - I N_0(E_F)} = S \chi_0 ,$$

where $N_0(E_F)$ is the unenhanced bare-band density of states at the Fermi energy and $\chi_0 = 2\mu_B^2 N_0(E_F)$. As the strength of the interaction $I N_0(E_F)$ increases, the paramagnetic

state becomes unstable with respect to a transition to the ferromagnetic state; the criterion for ferromagnetism in such systems is $IN_0(E_F) = 1$.

The imaginary part of $\chi(q, \omega)$ can be related to spin-spin correlation (3), and as the strength of the interaction increases, spin-spin correlation lifetimes are found to increase. It becomes possible to explain certain properties of the system in terms of itinerant damped spin fluctuations (paramagnons) with reasonably well defined energy-momentum relationships. In fact these paramagnons enter the theory in a manner similar to damped phonons and yield rather similar effects.

The emission and reabsorption of the paramagnons yield (4,5) contributions to the single-particle self-energy, and hence to the effective mass, rather similar to the manner in which the fermion-phonon interaction yields corrections to the effective mass. This leads not only to a modified low-temperature electronic heat capacity coefficient γ but to a modified temperature dependence (5) as well. In addition, s-electron scattering from d-electron spin fluctuations (paramagnons) has been shown to yield contributions to the low-temperature electrical and thermal resistivities which have been observed in several alloy systems.

The transition metals for which the theory has been specifically devised are those in which exchange enhancement effects are important but in which the system has not yet gone ferromagnetic. In this category are the pure metals palladium, platinum, and rhodium (and certain intermetallic compounds such as Ni_3Al and Ni_3Ga .) That these metals are easily polarizable can be deduced from the fact that not only do these metals have large paramagnetic susceptibilities but they can be made ferromagnetic by the addition of small amounts of either Fe or Co (6). Even more interesting is the observation that when nickel is added to Pd, Pt, or Rh, the systems remain paramagnetic over a limited concentration range with susceptibilities which increase with composition; this increase is most rapid for Pd and less rapid for either Pt or Rh. The compositions (in atomic percent) at which the three systems become ferromagnetic are $\approx 2\%$ for Pd (7), $\approx 40\%$ for Pt (8), and $\approx 60\%$ for Rh (9). The Stoner enhancement factors have not been precisely determined for each of these three metals, but they are in the same order as the ease with which the system can be made ferromagnetic, and the best estimates for S are ≈ 10 for Pd (10), $\approx 5/3$ for Pt (11), and ≈ 1 to $\approx 5/3$ for Rh (12).

In the paramagnetic region the magnetic susceptibility is a strong function of composition and diverges at the critical composition for the onset of ferromagnetism. In this composition region the Stoner enhancement factor increases and diverges in a similar manner. Because of the inability to distinguish between effects on S due to changes in $N_0(E_F)$ from alloying and effects on S due to changes in the interaction parameter I, it becomes convenient to define $\bar{I} = IN_0(E_F)$. As the critical composition is approached, \bar{I} approaches unity and the Stoner enhancement factor diverges.

Paramagnon interaction effects in alloys have been described in terms of two models which relate to the dependence of \bar{I} on composition. In the "uniform enhancement" theory no distinction is made between the solvent atoms and the solute atoms, and the interaction parameter \bar{I} is presumed to be the same throughout the solid. This approach has been devised specifically for pure metals which are exchange enhanced but has been extended to concentrated alloys in which sufficient averaging of atomic constituents is assumed to occur that the interaction parameter need be considered a function of only the composition. A second model, the "local enhancement" model (12-14), was specifically developed for the case of a host matrix containing a single impurity atom, like Ni, which tends to drive the system ferromagnetic. The basic interaction term in this case is taken to be particularly large in the cell containing the impurity atom; hence in this cell the system is more nearly ferromagnetic than elsewhere. This model is directly applicable to alloys

in the dilute limit; an extension to the case of more concentrated alloys also has been carried out (14).

Several experimental observations which have been attributed to paramagnon-interaction effects include (a) the very strong concentration dependence of the low-temperature electronic specific heat of *Rh*-Ni (9), *Pd*-Ni (15-17), and *Pt*-Ni (18) alloys, (b) the anomalous temperature dependence of the low-temperature specific heat of certain concentrated *Rh*-Ni alloys (9) and of one *Pd*-Ni alloy (19), and (c) the presence of a term proportional to T in the low-temperature thermal resistivity of dilute *Pd*-Ni alloys (20) and a term proportional to T^2 in the low-temperature electrical resistivity of dilute *Pd*-Ni (21) and *Pt*-Ni (18) alloys.

LOW-TEMPERATURE SPECIFIC HEAT

Theory

The first theoretical calculations which suggested that d -electron paramagnon interactions could lead to significant enhancement in the effective electronic mass were made almost concurrently by Berk and Schrieffer (4) and by Doniach and Engelsberg (5). Starting from an interaction term in the Hamiltonian as shown in Eq. (4) both groups calculated single-particle self-energy corrections due to the formation and reabsorption of paramagnons in the d -band. This yields, for a $T = 0$ calculation, an enhancement in the effective mass and hence in the low-temperature electronic heat capacity coefficient; carried to higher orders in the temperature this calculation leads to a modified temperature dependence of the low-temperature heat capacity as well.

The final results are

$$\frac{C_v}{T} = \left(\frac{m^*}{m}\right) \gamma_0 + \frac{6\pi^2}{5} \gamma_0 \frac{(S-1)^2}{S} \left(\frac{T}{T_s}\right)^2 \left(\ln \frac{T}{T_s}\right), \quad (6)$$

where (m^*/m) is the effective mass enhancement due to the many-body corrections to the self energy. Also,

$$\left(\frac{m^*}{m}\right) \approx 1 + \frac{9}{2} \ln(S/3) \quad (7)$$

and

$$T_s = (4T_F/\pi S \bar{I}), \quad (8)$$

where T_F is the Fermi temperature of the host matrix and T_s is a characteristic spin fluctuation temperature and is related to the peak (as a function of ω) of $\text{Im} \chi(\mathbf{q}, \omega)$ or to the peak of the spectral density function. As the interaction \bar{I} approaches unity, the Stoner enhancement factor increases rapidly and (m^*/m) should increase and T_s should decrease.

Experimentally this would be seen as a large increase (the theory suggests a divergence when $\bar{I} = 1$) in γ and the inclusion of a new temperature dependence for the low-temperature heat capacity which varies as $T^3 \ln T$. Experimental results of low-temperature heat capacity are usually analyzed by plotting (C/T) vs T^2 . On such a plot the data for simple metals yield straight lines; the intercept is γ , and the slope yields β , the coefficient of the lattice (Debye) term in the specific heat ($C = \gamma T + \beta T^3$). The

low-temperature specific heat, modified by paramagnon interactions, on the other hand, exhibits a modified behavior when plotted as C/T vs T^2 , namely an upturn which has a finite value and an infinite slope in the limit $T \rightarrow 0$.

All of these predictions are based on a uniform enhancement concept, one in which \bar{I} or S is the same throughout the metal lattice and can be increased uniformly. However, realistically, one can modify \bar{I} or S (at low temperatures) most easily by alloying with a solute which tends to make the system go ferromagnetic. If, as in the case of *Rh-Ni*, a considerable concentration of Ni is required before the system becomes ferromagnetic, sufficient averaging takes place that it appears reasonably correct to assume \bar{I} or S is uniform throughout the alloy. However, for *Pd-Ni* alloys, only $\approx 2\%$ Ni is required to make the system go ferromagnetic, and clearly a model which distinguishes between the solvent and the more magnetic solute atoms is required.

Two calculations have been made for such a system; in one (12) electron-electron interactions in the matrix have been neglected, and in the second (14) background electron-electron interactions have been included in the calculations. In both cases the calculations are based on an additional term in the Hamiltonian which accounts for the fact that the system is more nearly ferromagnetic in the vicinity of the single impurity atom than elsewhere in the lattice:

$$H_{\text{alloy}} = H_0 + \Delta I \sum_{\substack{\text{Ni} \\ \text{sites}}} n_{i\uparrow} n_{i\downarrow} \quad (9)$$

The increase in the electronic repulsion in the vicinity of the Ni atoms is phenomenologically introduced by the inclusion of the second term in Eq. (9); the first term is the Hamiltonian of the pure matrix, as in Eq. (4). The increase in the interaction parameter ΔI is empirically determined from the change in the magnetic susceptibility due to alloying. In the dilute limit (14)

$$\left. \frac{1}{\chi} \frac{d\chi}{dc} \right|_{c=0} = \frac{1}{\eta} = \frac{N_0(E_F) \Delta I}{1 - \Delta I \chi(r=0, \omega=0)} \quad (10)$$

where $\chi(r, \omega)$ is the transform of $\chi(q, \omega)$ for the pure matrix and c is the concentration of the impurity.

The spin polarizability of the matrix and the amplitude of the paramagnons are strongly enhanced in the vicinity of the impurity. This results in an additional increase in the value of γ and in the introduction of an additional term proportional to T^3 in the low-temperature specific heat. The calculation of Engelsberg et al. (14) yields

$$\frac{\Delta C_v}{T} = \frac{3c\gamma_0}{2\eta} \left[\left(\frac{1}{S} + \frac{\bar{I}\sigma}{3} \right)^{-1} + \frac{6\pi^2}{5} \bar{I}^2 S \left(\frac{T}{T_s} \right)^2 \ln \left(\frac{T}{T_s} \right) - \frac{9\pi^4}{20} n_e^2 \left(\frac{T}{\eta T_F} \right)^2 \left(\frac{1}{S} + \frac{\bar{I}\sigma}{3} \right)^{-3} \right] \quad (11)$$

where ΔC_v is the increase in the electronic heat capacity due to alloying, c is the concentration, η^{-1} (a localized-enhancement parameter) is $(1/\chi_{Pd})(d\chi_{\text{alloy}}/dc)$, σ is a range parameter for the host interaction (and is experimentally determined), T_F is the Fermi temperature for the host, and n_e is the number of d-electrons. The above result yields not only a mass enhancement term and a $T^3 \ln T$ term but a new term which varies as T^3 and in principle could add to the lattice heat capacity and yield a modified "concentration dependent Debye term."

A somewhat similar calculation has been made by Lederer and Mills (12). They consider the single-impurity case and assume that the intra-atomic repulsion between d-electrons is especially large in the cell containing the impurity atom but is insignificant elsewhere. Their calculation also yields the prediction that γ increases strongly and linearly with impurity concentration. Furthermore their calculation yields an upper limit to the increase in γ which is

$$\frac{1}{\gamma(\text{host})} \frac{d\gamma(\text{alloy})}{dc} = [3N(0)/N^*(0)] \left[\frac{1}{\chi(\text{host})} \frac{d\chi(\text{alloy})}{dc} \right], \quad (12)$$

where $N(0)$ is the bare band density of states of the host and $N^*(0)$ is the observed specific heat density of states of the host. They also note that the first correction to the linear specific heat term is proportional to T^3 , but they give no details.

An alternative treatment of enhancement effects considering local spin fluctuations in an exchange-enhanced host containing dilute impurities has been given by Chouteau et al. (17). The basic formula they quote for the predicted changes in the low-temperature electronic specific heat has the same functional form as Eq. (11), but it differs not only in certain analytical details but also in regard to the nature and intended use of the parameters. Chouteau et al. write for the extra specific heat per impurity atom

$$\frac{\Delta C_v}{T} \approx \Delta\gamma_0 \left[1 + \frac{6\pi^2}{5} \frac{S_{Pd}(S_{Pd}-1)}{\lambda} \left(\frac{T}{T_{s,0}} \right)^2 \ln \left(\frac{T}{T_{s,0}} \right) - \frac{4\pi^2}{5} \left(\frac{T}{T_{s,loc}} \right)^2 \right], \quad (13)$$

where

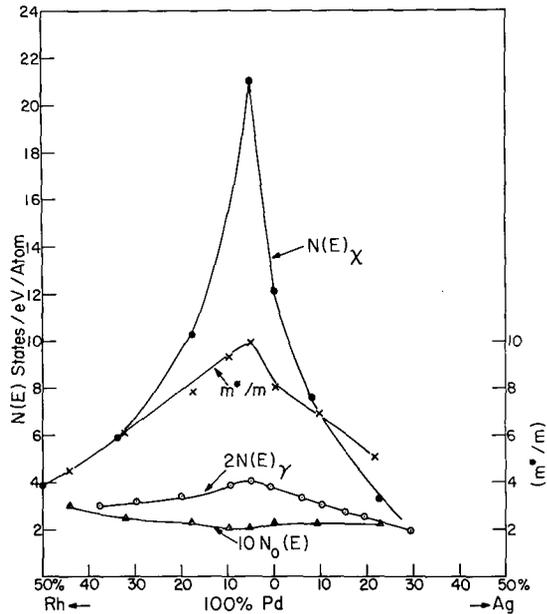
$$\lambda = \lim_{\omega \rightarrow 0} \frac{\sum_{\mathbf{q}} \text{Im } \chi_{Pd}(\mathbf{q}, \omega)}{\sum_{\mathbf{q}} \text{Im } \chi_0(\mathbf{q}, \omega)},$$

and $T_{s,0}$ is the characteristic paramagnon temperature of the host and equals $\approx [(\pi/4)(S-1)N_0(E_F)]^{-1}$. One of the differences between this treatment and that of Engelsberg et al. is the identification of a local fluctuation temperature $T_{s,loc}$. This term is treated as an experimentally determined quantity and can be obtained from the composition dependence of the "apparent lattice specific heat."

Experimental Results

The theoretical calculations of the effects of electron-paramagnon interactions on the electronic specific heat were originally applied (22) to old data of the heat capacity and magnetic susceptibility of the *Pd-Ag* and *Pd-Rh* alloy systems (23). It is well known that the values of both γ and χ of Pd containing about 5% Rh are significantly larger than those for pure Pd. Further additions of Rh to Pd result in a decrease in both χ and γ . A monotonic decrease in χ and γ is found for additions of Ag to Pd, the descent being most steep for alloys between pure Pd and Pd containing approximately 55% Ag. From these data, and using Eqs. (1) and (2), curves of $N(E_F)$ vs composition can be generated and are shown in Fig. 1.

Fig. 1 - The variation in the density of states $N(E)$ and the electron-paramagnon mass enhancement m^*/m of Pd-Rh and Pd-Ag alloys. $N(E)_\gamma$ and $N(E)_\chi$ are obtained from the measured values of the electronic specific heat coefficient γ and the magnetic susceptibility χ respectively. $N_0(E)$ is the unenhanced density of states obtained through the use of Eq. (6), and m^*/m is obtained through the use of Eq. (7), as explained in the text. For clarity $N(E)_\gamma$ and $N_0(E)$ have been multiplied by 2 and by 10 respectively.



The peaks in γ and χ originally were presumed to reflect a peak in the density of states curve in the 4-d band. In applying the paramagnon enhancement theory to these data, Berk and Schrieffer (22) assumed a Stoner enhancement factor of 50 for pure Pd. They were then able to deduce a mass enhancement factor for Pd of approximately 8. Extending this calculation to the Pd-Rh and Pd-Ag alloys, they concluded that the apparent peak in $N(E_F)$ was a result of spin fluctuation enhancement and that the bare band density of states of the d-band was relatively flat over the entire region under consideration (Fig. 1). Although they were forced to make many simplifying assumptions, among which are the assumptions of a single spherical band for the d-electrons and a much too large Stoner enhancement factor, the important conclusion of their work is that large mass enhancements can result from spin fluctuation interactions in the d-band.

The first heat capacity data to be taken specifically to observe electron-paramagnon mass enhancement effects were those of Ni-Rh alloys obtained by Bucher et al. (9). The magnetic susceptibility and heat capacity of this system are shown in Fig. 2. The region between pure Rh and 40%Rh-60%Ni is paramagnetic, and in this region the susceptibility increases in a manner consistent with enhancement theory for alloys near the critical concentration. The density of states obtained from the experimental values of the heat capacity is also increased and peaks around 63% Ni (which is actually on the ferromagnetic side of the critical concentration). Since such a high alloy concentration is necessary for the onset of ferromagnetism, it would appear appropriate to apply the uniform enhancement model to this system. Although both γ and χ are significantly enhanced, the authors indicate that the enhancement of χ at the critical concentration is ≈ 70 whereas the enhancement of γ is estimated to be only 2. This latter quantity is smaller by roughly a factor of 6 than the results of a calculation employing Eq. (7).

More significant, however, as shown in Fig. 3, is that an upturn is observed as $T \rightarrow 0$ when the heat capacity data are plotted as C/T vs T^2 . The authors are able to analyze the data using as the basic relationship an equation of the type of Eq. (6). The line drawn through the points at the lower temperatures is a fit using this expression.

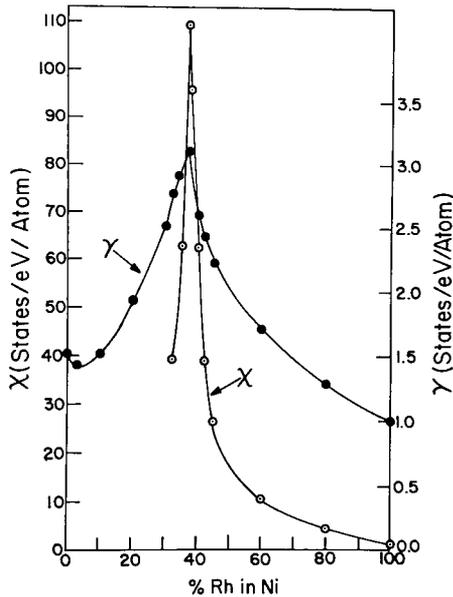
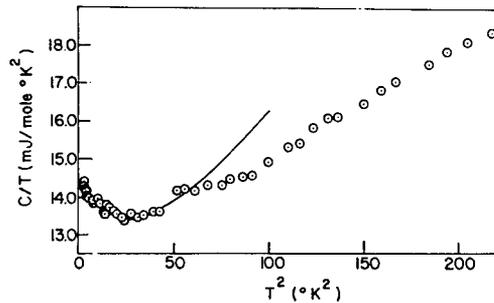


Fig. 2 - The magnetic susceptibility χ at 1.4°K and the electronic specific heat coefficient γ of Ni-Rh alloys

Fig. 3 - The specific heat versus temperature of a Ni-37%Rh sample. The solid line is a fit of the data using the expression $C/T = \gamma + aT^2 + bT^2 \ln T$.



Recent neutron diffraction observations of Hicks et al. (24) would indicate that near the critical concentration giant magnetization clusters are present. If this is the case, the low-temperature susceptibility would reflect superparamagnetic interactions between the clusters. Even more important is the fact that the increase in γ , as well as the "anomalous" temperature dependence, could be alternatively explained on the basis of superparamagnetic clusters.

At this moment the strongest corroboration of the theoretical calculations of mass enhancement due to electron-paramagnon interactions is that of the electronic specific heat of dilute Pd-Ni alloys (15-17,19). It is important to note that in this system the alloys of Pd containing between 0 and approximately 2% Ni are paramagnetic with susceptibilities that increase rapidly with increasing Ni concentration (15,16,25). From the measured values of the magnetic susceptibility as a function of concentration one finds $\chi^{-1} d\chi/dc = \eta^{-1} \approx 87$. The low-temperature heat capacity observed for this system is also extremely composition dependent; in plots of C/T vs T^2 , no upturn as $T \rightarrow 0$ is observed in the data for any of the specimens.*

*Fawcett et al. (19) have studied the low-temperature electronic specific heat of a Pd-1.89%Ni alloy over a relatively wide temperature range. At the lowest temperatures a slight nonlinear behavior suggestive of an upturn is observed.

For this reason, the data have been analyzed in terms of the usual formula $C = \gamma T + \beta T^3$, and the values of γ obtained by Schindler and Mackliet (15) and by Chouteau et al. (16) are shown in Fig. 4. The composition-dependent "apparent Debye term" obtained by Chouteau et al. (17) is shown in Fig. 5. For the dilute alloys γ is observed to increase extremely rapidly and linearly with concentration in accord with Eq. (11). The curve peaks, however, on the ferromagnetic side of the alloy system. Employing the experimentally determined values $\eta^{-1} \approx 87$ and $(1/\gamma) d\gamma/dc \approx 19$, and an estimated value 10 for S , one obtains for the range parameter σ a value of 10. This is to be compared with a value ≈ 6 for the corresponding quantity in pure Pd. Engelsberg et al. (14) feel that this is in good agreement with the theory, and they suggest that the increase in the value of the range parameter for dilute alloys represents changes in the exchange interaction in the vicinity of the impurity atoms.

Fig. 4 - Electronic specific heat coefficient γ in the low-temperature specific heat $C = \gamma T + \beta T^3$ as a function of composition of Pd-Ni alloys. Closed circles are from Ref. 15 and open circles are from Ref. 16.

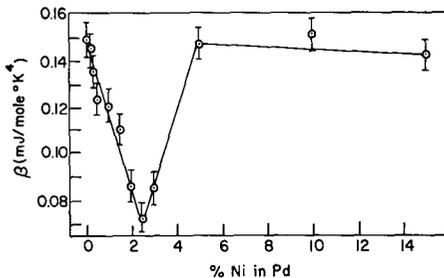
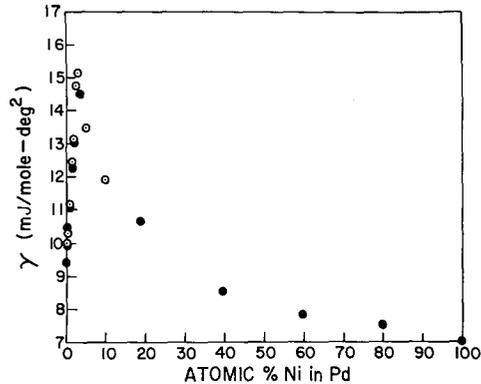


Fig. 5 - The coefficient β in the low-temperature specific heat $C = \gamma T + \beta T^3$ as a function of Ni concentration of Pd-Ni alloys

The fact that a $T^3 \ln T$ term is not observed, even for those alloys near the critical concentration for the onset of ferromagnetism, also can be understood by employing Eq. (11). The coefficient of the $T^3 \ln T$ term for dilute alloys is approximately that of pure Pd times a factor $3c/2\eta \approx 2.6$ for a 2% alloy. Since a $T^3 \ln T$ term is not observed in pure Pd, it is unlikely that it would be observed for the dilute, paramagnetic Pd-Ni alloys.

The same data have been interpreted in a related but somewhat different manner by Lederer and Mills (12) and by Chouteau et al. (17). Since Lederer and Mills employ a single impurity limit calculation, γ would be expected initially to vary linearly with composition, as is observed. The value of $(1/\gamma) d\gamma/dc$ can be obtained from Eq. (12). Assuming values $N^*(0)/N(0) \approx 2$ and $\eta^{-1} \approx 87$, one obtains as an upper limit a value 130 for $(1/\gamma) d\gamma/dc$. This is considerably larger than the experimentally determined value 19. (This apparent disagreement will be discussed later.) Also, Lederer and Mills note

that one should not expect to observe a $T^3 \ln T$ term for these alloys, which is in agreement with experiment.

Chouteau et al. also observe a concentration-dependent "apparent lattice term" in the specific heat which they attribute to two sources. One contribution they associate with the mass defect of the impurity and to the change in the elastic coupling. The other contribution they associate with the T^2 correction to the mass enhancement occurring in the local enhancement calculation (Eq. (13)). They show that the former contribution is small compared to the latter, and they then calculate a value of $20 \pm 4^\circ\text{K}$ for the local fluctuation temperature $T_{s, loc}$.

Electron-paramagnon enhancement of the electronic specific heat has been observed most recently in dilute alloys of the *Pt-Ni* system (18). The low-temperature heat capacities have been measured, and again it is found that the data can be analyzed in terms of the usual linear and cubic temperature dependence. The observed values for γ and β versus composition are shown in Figs. 6 and 7. The specific features which should be noted are (a) γ increases essentially linearly as a function of Ni concentration, with the data yielding $[1/\gamma(\text{Pt})] d\gamma(\text{alloy})/dc \approx 3$, and (b) the coefficient β of the T^3 term decreases significantly with increasing Ni concentration, the data yielding the rather rough estimate that, for the lower concentrations, $[1/\beta(\text{Pt})] d\beta(\text{alloy})/dc \approx -5 \pm 2$.

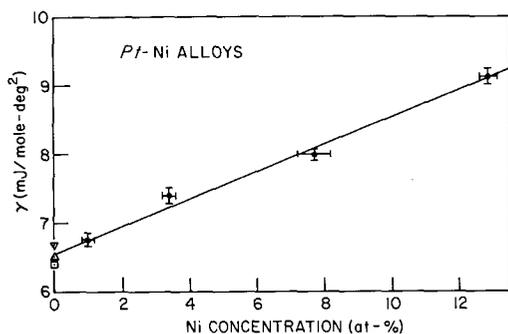
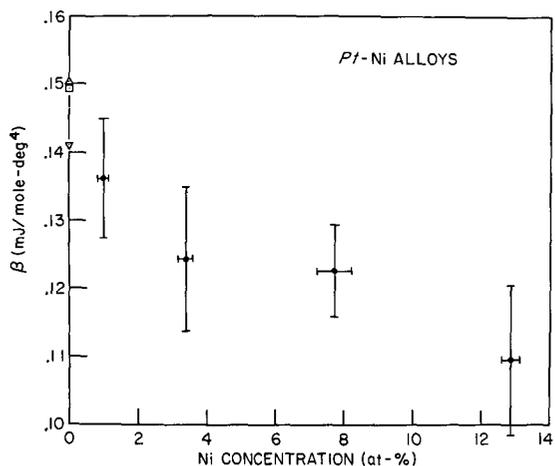


Fig. 6 - Concentration dependence of the electronic specific heat coefficient γ of dilute Pt-Ni alloys

Fig. 7 - Concentration dependence of the coefficient β of the T^3 term in the low-temperature specific heat of dilute Pt-Ni alloys



The large and linear increase in γ with composition is in qualitative agreement with the various model calculations of effective mass enhancement employing local-enhancement concepts. In the Lederer and Mills calculation, employing the theoretical estimates (11) $N^*(0)/N(0) \approx 3/2$ and $S \approx 5/3$ and the experimentally determined value $(1/\chi) d\chi/dc \approx 12$, one obtains a theoretical estimate $(1/\gamma) d\gamma/dc \approx 5$. This is to be compared with the experimental value 3. The theoretical calculation represents an upper limit for $(1/\gamma) d\gamma/dc$, and in a restricted sense the theory and experiment may at least be said to be consistent.

The calculation of Engelsberg et al. for local enhancement effects in a significantly-exchange-enhanced host yield a contribution to γ of the form

$$(1/\gamma) d\gamma/dc = (1/\chi) (d\chi/dc) (m^*/m)^{-1} (3/2) \left(\frac{1}{S} + \bar{I}\sigma/3 \right)^{-1}, \quad (14)$$

where m^*/m is the band mass enhancement factor of the host. Employing the appropriate values of the above quantities, one finds a value of the range parameter $\sigma \approx 25$. This value may be compared with the value 10 for *Pd*-Ni alloys and with the value 6 for pure *Pd*.

The work of Engelsberg et al. also predicts a low-temperature specific heat having a $T^3 \ln T$ term. One can estimate that for a Pt-6%Ni alloy the coefficient of this term is approximately 1. Therefore, since a $T^3 \ln T$ term is not observed for pure Pt, it follows that a $T^3 \ln T$ term is not expected to be observed in dilute *Pt*-Ni alloys.

A relatively linear variation with composition is found for the coefficient of the T^3 term in the specific heat, $(1/\beta) d\beta/dc \approx -5 \pm 2$. One can crudely estimate that the mass defect contribution to this term is ≈ -1 , leaving a substantial electron-paramagnon contribution. Employing Eq. (13), one finds for $T_{s,10c}$ a value ≈ 13 -25°K. This is to be compared with 20 ± 4 °K found for *Pd*-Ni alloys. Since the $T_{s,10c}$ parameter involves, in principle, not only the properties of the host matrix but also the properties of the impurity atom, it is difficult to assess the significance of the approximate equality of $T_{s,10c}$ for dilute *Pd*-Ni and *Pt*-Ni alloys.

It is to be noted that several of the theoretical estimates of the paramagnon enhancement of γ (or of m^*/m) are considerably larger than the experimentally observed values. This probably stems in part from the fact that the theoretical calculations are based on simplifying assumptions such as the presence of a single parabolic band and the presence of only intra-atomic exchange interactions between electrons. In recent theoretical work some of these problems have been considered including (a) Hund's rule coupling (26-28), (b) band structure effects (26,27,29), (c) impurity scattering effects (30,31) and (d) inter-atomic exchange interactions (27). Most of these considerations tend to decrease the theoretical estimates of mass enhancement and of the strength of the $T^3 \ln T$ term, although numerical estimates for the alloy systems which have been investigated experimentally are difficult to assess.

ELECTRON TRANSPORT PROPERTIES

Theory

The low-temperature electrical resistivity of strongly paramagnetic metals is composed of several contributions whose origins are well known. At low temperatures the electrical resistivity has the form

$$\rho = \rho_0 + AT^2 + G(T) , \quad (15)$$

where ρ_0 is the residual resistivity arising from electron-impurity scattering, AT^2 is an electron-electron scattering term, and $G(T)$ is the Grüneisen term arising from electron-phonon scattering and is proportional to T^5 at low temperatures:

$$G(T) = \nu (T/\theta_D)^5 J_5(\theta_D/T) \\ \approx BT^5 \quad \text{for } (T/\theta_D) \ll 1 ,$$

where $J_5(x)$ is the Bloch-Grüneisen integral and is

$$J_5(x) = \int_0^x \frac{y^5 dy}{(e^y - 1)(1 - e^{-y})}$$

(A, B, and ν are constants, and θ_D is the Debye temperature.)

The origin of the electron-electron scattering term AT^2 in Eq. (15), for all transition metals in general, was first given by Baber (32) and more recently by Appel (33) and Colquitt (34). Baber considered the case of electron-electron scattering via a screened coulomb interaction; no consideration was given to the initial or final spin states of the electrons. This mechanism gives rise to a significant resistivity contribution when a light, current-carrying electron (*s*-electron) is scattered by a massive electron (*d*-electron). The Baber calculation yields a term which varies as T^2 (as would be the case for all electron-electron scattering) and which increases as the ratio of the masses of the two electrons becomes greater than one.

The first calculation of the electrical resistivity arising from the scattering of *s*-electrons from itinerant *d*-electrons in which a spin flip of the electrons occurs was made by Mills and Lederer (35). They considered an exchange interaction of the form

$$H_{s-d} = V_c J \int s(\mathbf{r}) \cdot S(\mathbf{r}) d^3\mathbf{r} , \quad (16)$$

where V_c is the volume of the unit cell, J is the *s*-*d* interaction parameter, $s(\mathbf{r})$ is the spin density of the *s*-electrons, and $S(\mathbf{r})$ is the spin density of electrons in the *d*-band. They retain in Eq. (16) only the terms in which a spin-flip of an *s*-electron is described. They then calculate the relaxation time for a variety of cases; pertinent to this discussion is the case of a metallic, ferromagnetic system of itinerant spins at temperatures slightly above the Curie temperature. They demonstrate that the scattering rate and hence the resistivity should be proportional to T^2 (as contrasted with a constant term for localized spins); the magnitude of the T^2 term is not calculated. They observe that the results for this calculation should also apply to a paramagnetic metal, like Pd, at low temperatures.

Schindler and Rice (21) employed Eq. (16) and the Mills and Lederer formalism and attempted to estimate the coefficient of the T^2 term in the electrical resistivity for alloys in which the uniform enhancement model pertains.* They employed a variational principle (36) to solve the Boltzmann equation, and they related the scattering rate for

*They applied this model to dilute Pd-Ni alloys; this was later shown to be inappropriate.

s-electrons that scatter with a spin-flip from collective d-electron spin fluctuations to an integral equation containing the spectral density function for paramagnons. For the spectral density function, $A(\mathbf{q}, \omega)$, they employed a triangular approximation (37) which presumes a linear variation of $A(\mathbf{q}, \omega)$ with ω , up to a phenomenological cutoff value ω_q . (This approximation de-emphasizes high-frequency spin fluctuations and is a reasonably good approximation for strongly enhanced metals.) The calculations yielded a T^2 term in the electrical resistivity (and a term linear in T for the electron-electron scattering part of the thermal resistivity). The coefficient of the T^2 term was calculated to vary as S^2 , which for a uniformly enhanced system should, in turn, vary as $(X/X_0)^2$.

Lederer and Mills (13) have extended their earlier calculation to the case of a locally enhanced alloy system like Pd-Ni. Again they consider an enhanced matrix containing a single impurity atom which tends to drive the system ferromagnetic. The amplitudes of the low-frequency spin density fluctuations are enhanced in the vicinity of the impurity atom, and since this amplitude varies with temperature, they obtain a single impurity contribution to the resistivity which is found to vary as T^2 and as the first power of the concentration (in the dilute limit).

The expression they obtain for the composition dependence of the coefficient of the T^2 term is

$$A(c) = A(0) \{1 + \Gamma [s(\Delta I/I)]^2 c\}, \quad (17)$$

where $A(0)$ refers to the host matrix, Γ is a parameter which may be approximated in terms of n_d , the number of d-band holes and of S ($\Gamma \approx 1/4 n_d S^2$ for a Pd host and $1/6 n_d S^2$ for a Pt host), and s is a parameter which is expressed in terms of the real part of $X(\mathbf{q}, \omega)$ for the host, i.e.,

$$s^{-1} = 1 - \Delta I \sum_{\mathbf{q}} \chi_R(\mathbf{q}, 0),$$

and can be obtained from the susceptibility increase due to alloying ($\eta^{-1} = \Delta I \chi_0 s$). The calculation shows that, in the dilute limit, $A(c)$ varies linearly with concentration and has a slope that is roughly proportional to the square of the localized enhancement parameter η^{-1} .

More recently Schriempf et al. (2) have focused their attention on the effects of electron-electron scattering on the Lorenz number at low temperatures. Recall, as in Eq. (15), that

$$\rho = \rho_0 + AT^2 + bT^5,$$

where the electron-electron scattering term is AT^2 , and that the electronic thermal resistivity times the absolute temperature is

$$WT = (WT)_0 + \alpha T^2 + \beta' T^3,$$

where $(WT)_0$ is the electron-impurity scattering "residual" term, αT^2 is the electron-electron scattering contribution to the thermal resistivity, and $\beta' T^3$ is the electron-phonon scattering contribution to the thermal resistivity. The classical Sommerfeld value of the Lorenz number is just $\rho_0/(WT)_0 = L_s = 2.443 \times 10^{-8} \text{ V}^2/\text{K}^2$, and the electron-electron Lorenz number L_e is

$$L_e = \lim_{T \rightarrow 0} \frac{\rho - \rho_0}{(WT) - (WT)_0} = \frac{A}{\alpha}.$$

Schriempf et al. use the formalism of Mills and Lederer (35) but employ the procedure used by Schindler and Rice (21), i.e., a variational solution to the Boltzmann equation, and consider the contributions to the electrical resistivity of both spin-flip and non-spin-flip scattering of s-electrons from spin density fluctuations in the d-band. They calculate that, for low temperatures,

$$L_e = L_s \left[\frac{5}{3 + 12\beta(1)/\beta(3)} \right]. \quad (20)$$

Two forms of β are investigated, one appropriate to uniform enhancement, $\beta^{(U)}$, and one appropriate to local enhancement, $\beta^{(L)}$:

$$\beta^{(U)}(m) = \int_0^{2Q} x^{m-1} \left\{ 1 - \bar{I} \left[\frac{1}{2} h \left(\frac{k_s x}{2k_d} \right) \right] \right\}^{-2} |F(k_s x)|^2 dx \quad (21)$$

and

$$\beta^{(L)}(m) = \int_0^{2Q} x^m \left\{ \frac{N(0) \left[\frac{1}{2} h \left(\frac{k_s x}{2k_d} \right) \right]}{1 - \bar{I}_{Pd} \left[\frac{1}{2} h \left(\frac{k_s x}{2k_d} \right) \right]} \right\}^2 |F(k_s x)|^2 dx. \quad (22)$$

In these two expressions $F(q)$ is the form factor of the Wannier function associated with the unit cell at the origin and is obtained from the radial portion of the 4d(10) orbitals of atomic Pd calculated by Herman and Skilman (37), $h(x)$ is the Lindhard function, k_s and k_d are the Fermi wave vectors of the s- and d-electrons respectively, and $2Q$ is related to the maximum angle θ_M through which s-electrons are scattered, $2Q = \sqrt{2(1 - \cos \theta_M)}$. The electrical resistivity is also calculated with this model and is found to have the form

$$\rho_{ee} = \frac{3\pi^2 J^2 (k_B T)^2}{32 N \hbar e^2 V_s^2} \beta(3), \quad (23)$$

where N is the number of unit cells per unit volume and V_s is the Fermi velocity of the s-electrons.

To calculate the variation of L_e with alloying, k_d is treated as an adjustable parameter, and values of L_e and corresponding values of ρ_{ee} are obtained. The results are given as graphs in the form of L_e vs $(A_{\text{alloy}} - A_{\text{Pd}})/A_{\text{Pd}}$. (Calculations appropriate to Pd-Ni alloys will be included as solid curves for comparison with experimental data in Fig. 12.)

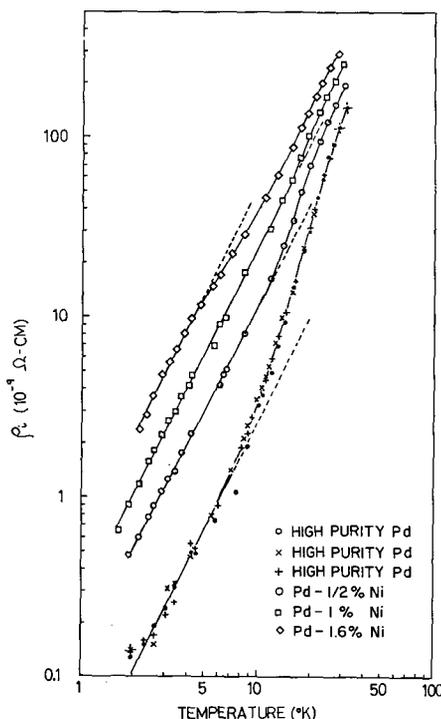
Experimental Results

Electron-paramagnon scattering effects have been observed, thus far, in only Pd-Ni and Pt-Ni alloys. In both cases the local enhancement model seems most appropriate,

since only dilute alloys have been investigated; in the *Pd*-Ni system, alloys containing up to $\approx 2\%$ Ni were investigated,* and in the *Pt*-Ni system, alloys containing up to 9.4% Ni were examined.

The ideal electrical resistivity $\rho - \rho_0$ of *Pd*-Ni versus the absolute temperature T is shown in Fig. 8 on a log-log plot. The straight line sections of the curves all have slopes of 2; the coefficients A increase with increasing composition.

Fig. 8 - The ideal electrical resistivity as a function of temperature



The coefficient A of the T^2 term is plotted versus composition in Fig. 9. The initial increase is approximately linear, but then A climbs more rapidly as the critical composition is approached. The value of $(1/A)dA/dc$ for *Pd*-Ni is found to be ≈ 675 . The experimentally observed linear variation of A with composition is in agreement with the linear variation predicted by the Mills and Lederer calculation, and the experimental value of $(1/A)dA/dc$ corresponds closely with the theoretical estimate. One obtains a value $(1/A)dA/dc \approx 700$ from Eq. (17) with the estimates $\eta^{-1} = 87$ (25), $s = 10$, and $n_d = 0.3$ hole/atom. This rather good agreement between theory and experiment leads one to believe that s -electron-paramagnon scattering is the dominant contribution to the electron-electron term in the low-temperature electrical resistivity of pure Pd.

The low-temperature electrical resistivity of dilute *Pt*-Ni alloys is shown as a function of composition in Fig. 10 along with values of the residual resistivity. A linear variation of A with composition is observed up to approximately 2% Ni. For the quantity $(1/A)dA/dc$ these experiments yield a value ≈ 28 . The observed linear variation of A with

*The data presented here represent the data of Ref. 21 plus additional new data of Schindler and La Roy.

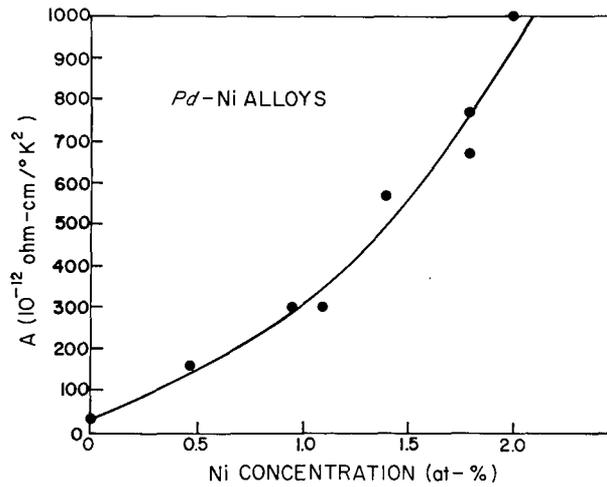


Fig. 9 - Concentration dependence of the coefficient of the T^2 term in the low-temperature electrical resistivity $\rho = \rho_0 + AT^2 + BT^5$ of dilute Pd-Ni alloys

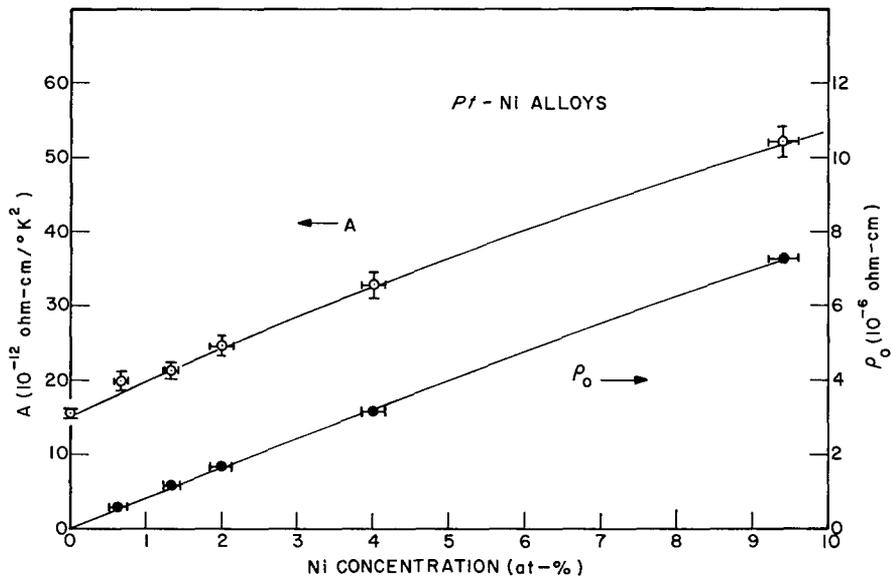


Fig. 10 - Concentration dependence of the residual resistivity and of the coefficient of the T^2 term in the low-temperature electrical resistivity $\rho = \rho_0 + AT^2$ of dilute Pt-Ni alloys

composition is again in agreement with the Mills and Lederer calculation; however, a larger value of $(1/A)dA/dc$ is predicted. Reasonable estimates of the necessary parameters are $n_d(\text{Pt}) \approx 0.4$ hole/atom,* $S(\text{Pt}) \approx 5/3$ (11), and $\eta^{-1} \approx 10-12$ (40). With these parameters one obtains $(1/A)dA/dc_P \approx 55$, where the subscript P serves to emphasize that this calculation gives only the spin-fluctuation contribution. The experimentally determined value of $(1/A)dA/dc$, on the other hand, includes all types of electron-electron scattering, including those which do not result in spin flips. The difference between experiment and theory can be resolved if one assumes the presence of an additional, concentration-independent contribution to the electrical resistivity having the form $A'T^2$, where $A' \approx (1/2)[A(\text{Pt})]_{\text{expt}}$. A term of this type might well arise from non-spin-flip (Baber) electron-electron scattering.

A term, linear in temperature, in the thermal conductivity, representing the electron-electron scattering contribution, has only recently been observed for rather pure Pd (41). From an experimental point of view the observation of such a term for alloys is expected to be complicated by the possible presence of a significant amount of heat transport via the lattice. However, in the dilute Pd-Ni alloy system the electron-electron contribution would be expected to be sufficiently large that it would still be discernible in the presence of a lattice heat conduction of typical size for transition metal alloys. In other, less enhanced, alloy systems the detailed behavior of the electron-electron term would be expected to be masked by the phonon term.

Thermal and electrical resistivity measurements of Pd containing up to 1% Ni have been made between ≈ 2 and $\approx 20^\circ\text{K}$ by Schriempf et al (20). Beyond the composition Pd-1%Ni the electron-electron term in the thermal resistivity could not be detected with any accuracy. The thermal resistivity results are shown in Fig. 11; the electrical resistivity data are in agreement with those already discussed for this system. The thermal resistivity data are plotted in such a way that the intercept yields the coefficient α of the T^2 term of WT . The coefficient α increases rapidly with composition in a manner similar to the behavior of A .

Values of L_e versus $\delta A/A$, where $\delta A = A_{\text{alloy}} - A_{\text{Pd}}$, are shown in Fig. 12. It is seen that the value of L_e is essentially constant with composition. Theoretical values of L_e for both the uniform and the average enhancement models have been calculated using Eqs. (20), (21), and (22), and the results are shown as the solid lines. A value of $k_s = 9.125 \times 10^7 \text{ cm}^{-1}$, $k_d = 2k_s$, and $\bar{I}_{\text{Pd}} = 0.9$ were used in the calculation. The largest discrepancy between theory and experiment is seen to be at pure Pd. It is felt that this discrepancy is a result of the omission of a Baber scattering contribution to the resistivity. An estimate of Baber scattering was made (90% of the scattering in pure Pd), and the same amount was added to the resistivities of the Pd-Ni alloys. The result of this modification is shown in the figure as the dashed line. The agreement is better but still not excellent.

SUMMARY

Electron-paramagnon interaction contributions to several physical properties of strongly-exchange-enhanced alloys have been observed. Theoretical calculations of these effects give, in almost all cases, reasonable, but somewhat large, estimates for their magnitudes. Comparisons of the experimental observations and the corresponding theoretical analyses are as follows.

*A rough estimate of $n_d(\text{Pt})$ was obtained from the size of the Γ -centered, closed electron surface in Pt (38,39).

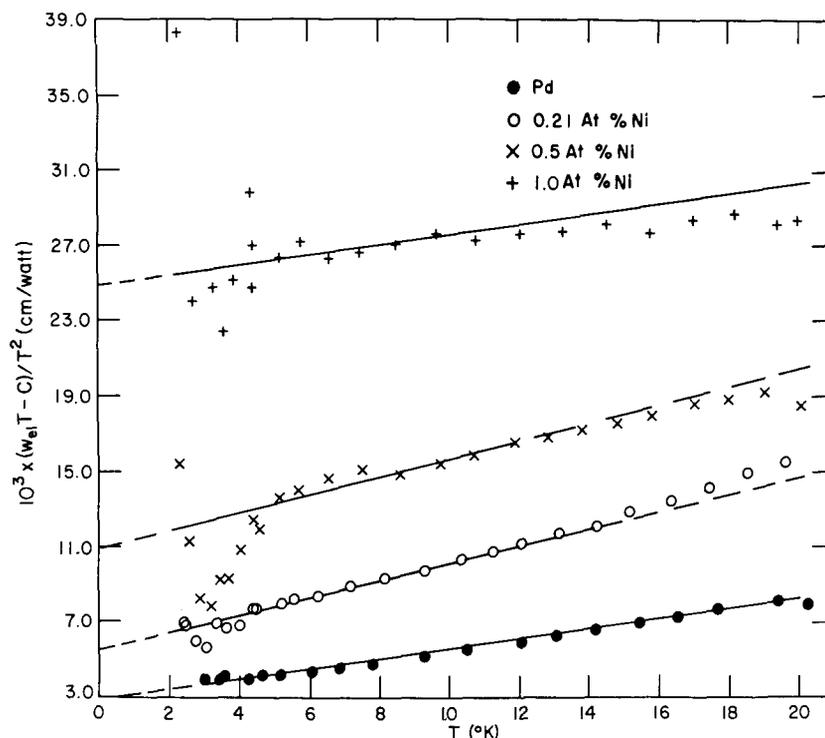


Fig. 11 - The electronic thermal resistivity of Pd-Ni alloys as a function of the absolute temperature

1. The coefficient γ of the electronic specific heat is found to be strongly composition dependent for dilute, exchange-enhanced alloy systems. A linear variation of γ with composition is found for dilute Pd-Ni and Pt-Ni alloys. In both alloy systems the magnitudes of the increase of γ with composition are considerably smaller than the theoretical estimates.

2. The coefficient γ of Rh-Ni alloys is also found to be strongly composition dependent near the critical composition for the onset of ferromagnetism. The increases of both γ and χ are similar in appearance (they both exhibit maxima at the same composition), but the theoretical estimate of the enhancement in γ is significantly larger than is experimentally observed.

3. Theory predicts the presence of a $T^3 \ln T$ term in the low-temperature specific heat. Such a term is found in the specific heat of Rh-Ni alloys (and possibly in one Pd-Ni alloy) but is most apparent in a Rh-Ni alloy which has already gone ferromagnetic.

4. Theoretical calculations predict a composition-dependent "Debye" term. Such a term is observed for dilute Pd-Ni and Pt-Ni alloys.

5. The low-temperature electrical resistivity of dilute Pd-Ni and Pt-Ni alloys contains a T^2 term with a coefficient A which is an extremely strong function of the composition. A linear behavior is observed at low concentrations in agreement with the local enhancement model. The correspondence of the experimental and theoretical estimates for $(1/A) dA/dc$ for Pd-Ni alloys is especially good. This suggests that in these alloys the AT^2 term is dominated by electron-paramagnon scattering. Theoretical estimates

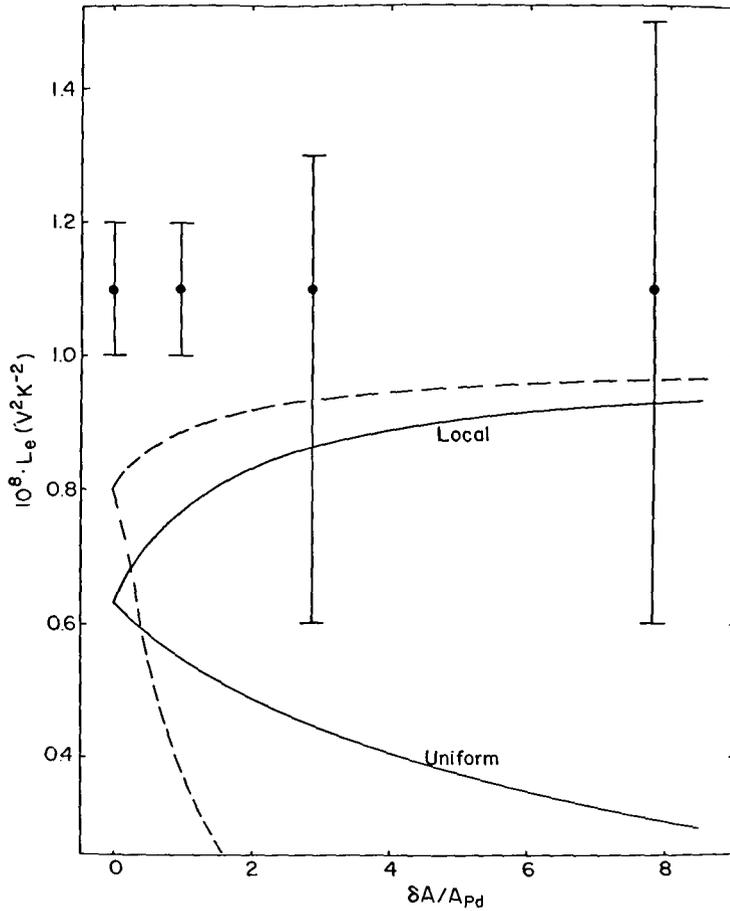


Fig. 12 - Comparison of calculated and measured values of L_e of Pd and dilute Pd-Ni alloys. A is the coefficient of the T^2 term in the electrical resistivity, and $\delta A = A_{\text{alloy}} - A_{\text{Pd}}$. The solid dots and error bars represent values of L_e extracted from the data. The solid lines are the results of calculations for both local and uniform enhancement models of electron-paramagnon scattering with $\bar{I}_{\text{Pd}} = 0.9$, $k_s = 9.125 \times 10^7 \text{ cm}^{-1}$, and $k_d = 2k_s$. The dashed lines are the results of modifying the calculation by adding a concentration-independent amount of Baber scattering to the electron-paramagnon scattering; the dashed curves shown here are for Baber scattering which is 90% of the scattering in pure Pd.

of the magnitude of the linear dependence of A with composition for dilute *Pt*-Ni alloys are somewhat larger than the experimental values, but agreement can be obtained if a reasonable amount of Baber scattering is assumed to be present in pure *Pt* and in the dilute alloys.

6. The low-temperature thermal resistivity of dilute *Pd*-Ni alloys is found to contain a term linear in temperature, which is in accord with the electron-electron scattering calculation. The coefficient of this term is a strong function of composition and yields a value of L_e which is essentially independent of the composition. Theoretical estimates of the variation of L_e are obtained which agree tolerably well with experiment, if the local enhancement model is employed. To obtain agreement it is found necessary to assume $k_d = 2k_s$ and to assume that, in contrast with the conclusions of earlier observations, a significant amount of Baber scattering is present in pure *Pd*.

ACKNOWLEDGMENTS

The author is indebted to C. A. Mackliet, J. T. Schriempf, and D. J. Gillespie for many helpful discussions and for their assistance in the preparation of this report.

REFERENCES

1. Stoner, E.C., Proc. Roy. Soc. 165A, 372 (1938); 169A, 339 (1939)
2. Izuyama, T., Kim, D.J., and Kubo, R., J. Phys. Soc. Japan 18, 1025 (1963)
3. Doniach, S., Proc. Phys. Soc. 91, 86 (1967)
4. Berk, N.F., and Schrieffer, J.R., Phys. Rev. Letters 17, 433 (1966)
5. Doniach, S., and Engelsberg, S., Phys. Rev. Letters 17, 750 (1966)
6. Crangle, J., "Electronic Structure and Alloy Chemistry of Transition Elements," P. Beck, editor (Interscience, New York, 1963), p. 51
7. Bozorth, R.M., Davis, D.D., and Wernick, J.H., J. Phys. Soc. Japan 17, Suppl. B-1, 112 (1962)
8. Gillespie, D.J., and Schindler, A.I., private communication
9. Bucher, E., Brinkman, W.F., Maita, J.P., and Williams, H.J., Phys. Rev. Letters 18, 1125 (1967)
10. Mueller, F.M., Freeman, A.J., Dimmock, J.O., and Furdyna, A.M., to be published
11. Mueller, F.M., Garland, J.W., Cohen, M.H., and Bennemann, K.H., to be published
12. Lederer, P., and Mills, D.L., Phys. Rev. Letters 20, 1036 (1968)
13. Lederer, P., and Mills, D.L., Phys. Rev. 165, 837 (1968)
14. Engelsberg, S., Brinkman, W.F., and Doniach, S., Phys. Rev. Letters 20, 1040 (1968)
15. Schindler, A.I., and Mackliet, C.A., Phys. Rev. Letters 20, 15 (1968)
16. Chouteau, G., Fourneaux, R., Gobrecht, K., and Tournier, R., Phys. Rev. Letters 20, 193 (1968)
17. Chouteau, G., Fourneaux, R., Tournier, R., and Lederer, P., Phys. Rev. Letters 21, 1082 (1968)
18. Mackliet, C.A., Schindler, A.I., and Gillespie, D.J., Phys. Rev., to be published
19. Fawcett, E., Bucher, E., Brinkman, W.F., and Maita, J.P., Phys. Rev. Letters 21, 1183 (1968)
20. Schriempf, J.T., Schindler, A.I., and Mills, D.L., Phys. Rev. 187 (1969); also NRL Report 6949, Sept. 15, 1969

21. Schindler, A.I., and Rice, M.J., Phys. Rev. 164, 759 (1967); Schindler, A.I., and Coles, B.R., J. Appl. Phys. 39, 956 (1968)
22. Berk, N.F., and Schrieffer, J.R., Proc. 10th Intern. Conf. on Low Temp. Phys. Moscow, 1966, Moscow, Viniti, 1967, Vol. IIA, 150-156
23. Hoare, F.E., and Preston, J., Nature 180, 334 (1957)
24. Hicks, T.J., Rainford, B., Kouvel, J.S., Low, G.G., and Comly, J.B., Phys. Rev. Letters 22, 531 (1969)
25. Shaltiel, D., Wernick, J.H., Williams, H.J., and Peter, M., Phys. Rev. 135, A1346 (1964)
26. Doniach, S., Phys. Rev. Letters 18, 554 (1967)
27. Schrieffer, J.R., Phys. Rev. Letters 19, 644 (1967)
28. Caroli, B., Lederer, P., and Saint-James, D., Phys. Rev. Letters 23, 700 (1969)
29. Schrieffer, J.R., J. Appl. Phys. 39, 642 (1968)
30. Fulde, P., and Luther, A., Phys. Rev. 170, 570 (1968)
31. Brinkman, W.F., and Engelsberg, S., Phys. Rev. Letters 21, 1187 (1968)
32. Baber, W.G., Proc. Roy. Soc., A158, 383 (1937)
33. Appel, J., Phil. Mag. 8, 1071 (1963)
34. Colquitt, L., Jr., J. Appl. Phys. 36, 2454 (1965)
35. Mills, D.L., and Lederer, P., J. Phys. Chem. Solids 27, 1805 (1966)
36. Ziman, J.M., "Electrons and Phonons," Clarendon Press, Oxford, 1960, Ch. 7
37. Herman, F., and Skillman, S., "Atomic Structure Calculations," Englewood Cliffs, N.J., Prentice-Hall 1963
38. Ketterson, J.B., Phys. Rev. Letters 20, 324 (1968)
39. Windmiller, L.R., Ketterson, J.B., and Hornfeldt, S., Jr., J. Appl. Phys. to be published
40. Thorpe, A., and Sullivan, S., private communication; Launois, H., Thesis, Univ. of Paris, unpublished
41. Schriempf, J.T., Phys. Rev. Letters 19, 1131 (1967); 20, 1034 (1968)